

Monitoring the Influence of Sodium Chloride Particle Size on the Physical, Mechanical Properties and Structure of Samples of Porous Aluminium Materials

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The paper deals the production of porous aluminum materials that are characterized by lower density and mechanical properties. Samples of porous aluminium materials were produced on the basis of the developed methodology that applied sodium chloride particles of different sizes (average size 4, 6 and 9 mm). The AlSi12 foundry alloy was preferred for the production of the aluminium porous material. As part of the experiments, samples of porous aluminium material in the shape of a truncated cone were made. The cavity of the foundry mould was in the shape of a truncated cone with diameters: $D = 0.047$ m, $d = 0.040$ m and height $v = 0.040$ m. The material properties were determined on the produced samples. Their weight, volume and their density, relative density were calculated. Based on empirical relations, their value of Young's modulus of elasticity and value of thermal conductivity were determined. The compressive strength of selected samples was monitored as well. The value of Young's modulus of elasticity was determined from the measured stress-strain course. Furthermore, the porosity of the produced samples was evaluated on a scanning microscope.

Keywords: Porous aluminium materials, Sodium chloride, Relative density, Compressive strength, Young's tensile modulus.

1 Introduction

Currently the metallurgical industry focuses on the production of lightweight metal materials which must be also environmentally friendly. Lightweight metallic materials are referred to in the literature primarily as cellular metallic systems, most commonly referred to as "metallic" foams". The idea of manufacturing metal cellular systems (metal foams) dates back to 1926. Other sources state that the origin of cellular metal systems dates back to the 1940s DE MILLER [1]. HALBART [2], [3] states that there are four most commonly used basic types of "metal foam" production (direct melt foaming; controlled solidification of the melt in a supersaturated gas atmosphere; powder metallurgy; foundry methods).

Foundry methods can be divided into three basic groups; lost body casting, filling material casting [4] and replication process, [4, 5, 6].

2 Process of production of porous aluminium materials

The first report on the replication process was issued in the early 1960s, and since then the development of the research group at the Swiss Federal Institute of Technology in Lausanne has evolved in various stages. Luna [6] publishes the whole process of this method in detail. This method is based on the use of vacuum which became to be a standard method for

the production of "open cell metal foams" at the Department of Materials Engineering, University of Sheffield. At the same time, further research was carried out at this workplace and two other new methods called gas and mechanical infiltration were introduced. Metal cellular systems (porous metals and metal foams) are expanded metal materials that contain intentionally created pores in their structure that means aluminium porous materials, also referred to as "open-cell aluminium foams." These porous materials contain many free spaces called as pores or cavities in their structure. The size of the pores varies from a few nanometers to many millimetres and the size depends on the purpose of the porous material. In mechanical engineering, a homogeneous material is often preferred, but in the natural world the reverse effect occurs, which means that the pores have different sizes in the same structure, which is defined as the porosity gradation [8], [9], [10], [11].

The characterization of the porous material depends on the pore size according to IUPAC (International Union of Pure and Applied Chemistry); ROQUEROL [12] and LIU [13] mention three classifications of microporous, mesoporous and macroporous materials) and particular definitions are given in publications [12], [13]. The macroporous material has a pore size greater than 50 nm; it is commonly used for filters, anode material for fuel cells, stationary phases for various types of chromatography, bi-

oreactors, microfluidic chips, filtering and heat transfer applications [15].

In foundry processes in the production of aluminium cellular materials, attention must be paid to their metallurgical preparation [14, 16]. Open-cell metallic "foams", also referred to as porous metallic materials. These materials contain so-called open cells with adapted porous morphology based on particles of substances such as sodium chloride. These NaCl particles are filled with a melt of metal alloys, such as aluminium. By solidification of these metal melts, a heterogeneous system is formed consisting of metal and sodium chloride particles. Various technologies are used in the production of porous materials, [17], [18], [19], [20]. Other research preferred instead of sodium chloride particles of sand bound, for example, by furan resin or ceramic particles bound by gypsum. In all manufacturing methods, the mechanism by which the melt penetrates between the particles of the substance that define the cavities in the porous material is important. The most common method is infiltration of molten metal, also called the replication process [21].

Spherical granular urea as space holders was adopted for a production of porous materials based on powder metallurgy [22]. Another research work [23] focussed on corrosion effects for aluminium alloys, which are the basis of the production of porous materials. Our published work [24] deals with the monitoring of other possibilities for porous aluminium material production and the evaluation of their physical properties of such produced materials. The evaluation of the properties of porous materials was also dealt with by LUNA [6] and the most common physical quantities were found to be: the actual density, which is the density of the material without pores or cavities; bulk density is the density of the material, including open pores and cavities; pore volume is the addition of individual pore volumes; pore size is the

distance between the walls of the pores, their width or diameter; porosity is the relationship between the total pore volume to the apparent volume of a sample or particle and the final surface area, which is the surface area of the non-porous material.

Within the use of sodium chloride for our research, knowledge about its properties published [25], on thermogravimetric (TG) and Differential Scanning Calorimetry analysis (DSC) was used. The melting point of sodium chloride at 802 °C was confirmed, which is sufficient for the experiments of aluminium and sodium chloride alloys.

3 Experimental production of aluminium porous materials

Based on the above theoretical analysis, it is clear that the successful production of aluminium porous materials using sodium chloride must be based, for example, on the use of a vacuum system and inert gas (argon). Production of porous aluminium materials using sodium chloride particles (salt cores), resp. space holder particles (SHP) method is most often based on the melt infiltration process. Our experiments summarized below are based on the pressing of sodium chloride particles into the aluminium melt. For this purpose, an aluminium alloy (EN AC-44300) AlSi 12 (melting point approx. 577 °C) was used and the density is 2650 [kg·m⁻³]. This method was used e.g. in publication [24] in which the production of porous aluminium material by pressing the melt between sodium chloride particles and evaluating the properties of the material produced was introduced. This publication presents the results of the production of an aluminium porous material by pressing sodium chloride particles into this melt. The chemical composition of used aluminium alloy AlSi12 was identified by a Bruker Q4 Tasman optical emission spectrometer – see Tab. 1.

Tab. 1 Chemical composition of used AlSi12 aluminium alloy

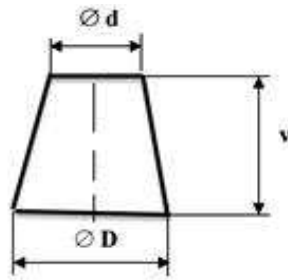
Chemical composition of aluminium alloy EN AC 44300 (AlSi12) [wt %]										
Si	Fe	Mn	Cu	Zn	Ti	V	Mg	Na	Pb	Al
According to EN ČSN										
10.5-13.5	0.45-0.90	0.55	0.08	0.15	0.15	-	-	-	-	-
Real chemical composition of used alloy										
12.1	0.43	0.46	0.04	0.12	0.1	0.007	0.001	0.005	0.004	86.96

A steel foundry mould (steel ČSN EN 1.2343) was used for the production of aluminium porous materials by pressing sodium chloride into an AlSi 12 aluminium alloy melt, see Fig. 1 (left). The cavity of the mould was in the shape of a truncated cone, as demonstrated in Fig. 1 (right).

For the production of aluminium cellular system a combination of a foundry method using a filler material was adopted for the porous aluminium alloy. This

material was sodium chloride of three sizes (see Fig. 2): 4 mm; 6 mm and 9 mm (3 to 5 mm; 5 to 7 mm and 8 to 10 mm).

The cavity contained the half of the sodium chloride and half of the AlSi 12 alloy. Table 2 shows the calculated values of the weight of sodium chloride and AlSi 12 alloy



$\varnothing D = 0,047 \text{ m}$; $\varnothing d = 0,040 \text{ m}$; $v = 0,040 \text{ m}$

Fig. 1 Used foundry mould for the production of porous metals (on the left); schema of its cavity (on the right)



Fig. 2 Sodium chloride particle sizes for the production of aluminium porous materials (average salt particle size 9 mm, 6 mm and 4 mm).

The AlSi 12 alloy was melted in a graphite crucible in a "Classic" resistance melting furnace. The superheat temperature of the melt was varying between 720 and 750 °C. Before the onset of casting process into the foundry mould, the melt was metallurgically treated with refining salts. After measuring of the temperature, the melt was poured into the foundry mould. Prior to pouring the melt into the mould cavity, the mould was preheated to the operating temperature and treated with a protective graphite spray (Molyb-kombin UMF T4 spray). Then, a measured amount of the AlSi12 alloy melt was poured into the preheated foundry mould and finally, a measured amount of sodium chloride was poured into the mould, see Fig. 3 (left and middle). This mould containing the melt and sodium chloride was placed under a hydraulic press. The sodium chloride was pressed into the aluminium alloy melt with a punch (see Fig. 3 right). To push the sodium chloride particles into the aluminium alloy melt, it is important that a pressure of approximately 80 MPa is exerted on the sodium chloride. At the same time, it is necessary that the hydraulic press must be setting for this particular pressure level.

Tab. 2 Calculated values weight of sodium chloride and AlSi12 alloy

Calculation of sodium chloride weight		
Weight NaCl m_{NaCl} [kg]	Volume NaCl V_{NaCl} [m ³]	Density NaCl ρ_{NaCl} [kg·m ⁻³]
0.065	$2.987 \cdot 10^{-5}$	2165
Calculation of AlSi 12 aluminium alloy weight		
Weight AlSi12 m_{AlSi12} [kg]	Volume AlSi12 V_{AlSi12} [m ³]	Density AlSi12 ρ_{AlSi12} [kg·m ⁻³]
0.079	$2.987 \cdot 10^{-5}$	2650

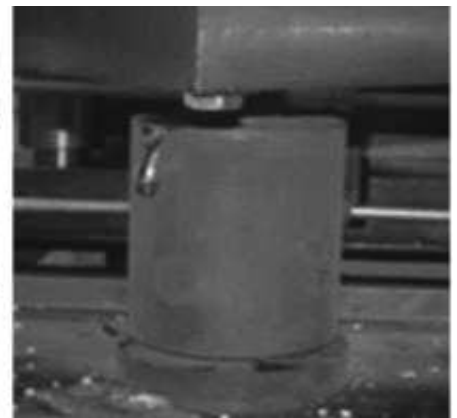
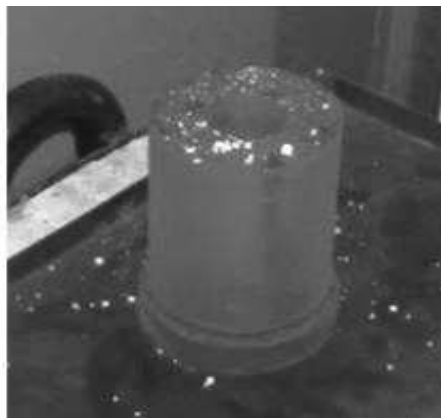
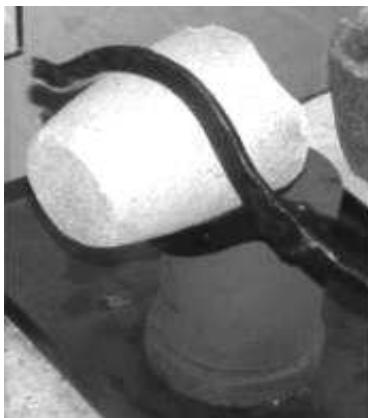


Fig. 3 Pouring the melt into the foundry mould, pouring NaCl into the mould and pressing NaCl into the AlSi 12 melt

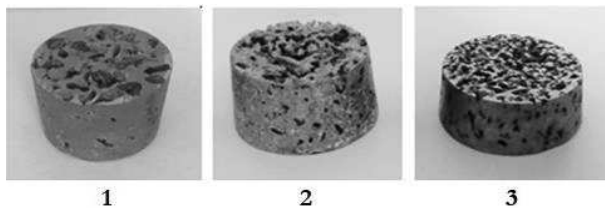


Fig. 4 Manufactured samples of porous aluminium materials from AlSi12 alloy in the shape of a truncated cone

In Figure 6 and 7, porous materials are produced using both types of sodium chloride particles by pressing them into an AlSi12 melt.

The produced samples of porous aluminium materials were analyzed, physical values were calculated on the basis of their material characteristics and particular values are given in Table 3.

Tab. 3 Basic dimensions and density of produced samples from aluminium porous material

Basic dimensions and density of produced samples from aluminum porous material							
Sample identification	Size particles NaCl [mm]	Basic dimensionlas of the sample			V alues for density calculation		
		Diameter D [mm]	Diameter d [mm]	Height h [mm]	Mass sample m [kg]	Volume sample V [m ³]	Sample density ρ [kg·m ⁻³]
1	8 to10	45.5	41.2	26.8	0.0379	4.057·10 ⁻⁵	934
2	5 to7	46.5	42.3	25.0	0.0385	3.872·10 ⁻⁵	994
3	3 to 5	46.0	44.1	20.45	0.0354	3.258·10 ⁻⁵	1086

3.1 Evaluation of the properties of a porous material made of aluminum alloy AlSi12 produced by *pressing NaCl into a melt of aluminum alloy*

To evaluate the properties of the produced porous aluminium materials, we developed a methodology which was published [24]. This methodology is primary used for determining of the relevant physical and material characteristics, respectively relevant quantities. The evaluation of the produced aluminium porous materials concerns the determination of the following quantities:

Determination the density of the porous AlSi12 alloy ($\rho_{P.(AlSi12)}$) – it is determined by physical calculation according to the following relation:

$$\rho_{P.(AlSi12)} = \frac{m_{P.(AlSi12)}}{V_{P.(AlSi12)}}, \quad (1)$$

Where:

$\rho_{P.(AlSi12)}$Density of the porous AlSi12 alloy [kg·m⁻³],

$m_{P.(AlSi12)}$Weight of the porous AlSi12 alloy [kg],

$V_{P.(AlSi12)}$Volume of the porous AlSi12 alloy [m³].

Determination the relative density of the porous AlSi12 alloy ($\rho_{REL.(AlSi12)}$):

$$\rho_{REL.(AlSi12)} = \frac{\rho_{P.(AlSi12)}}{\rho_{B.(AlSi12)}}, \quad (2)$$

Where:

$\rho_{REL.(AlSi12)}$..Relative density of porous AlSi12 alloy [1],

$\rho_{P.(AlSi12)}$Density of porous AlSi12 alloy [kg·m⁻³],

$\rho_{B.(AlSi12)}$Density of the base AlSi12 alloy (without porosity) [kg·m⁻³].

Determination the density of discretized structure of the porous AlSi12:

$$\rho_{P.(AlSi12)} = \frac{\rho_{B.(AlSi12)} \cdot V_{P.(AlSi12)}}{V_{B.(AlSi12)}}, \quad (3)$$

here:

$V_{B.(AlSi12)}$...Volume of the base AlSi12 alloy (without porosity) material [m³].

Determination the porosity of porous AlSi12 alloy (P or ϵ):

It is the ratio of density difference between base AlSi12 alloy and porous AlSi12 (porous AlSi12 – $P.(AlSi12)$) to density of base (non-porous) AlSi12 ($B.(AlSi12)$):

$$P = \left(1 - \frac{\rho_{P.(AlSi12)}}{\rho_{B.(AlSi12)}}\right) \cdot 100 [\%] \quad (4)$$

Determination the Young's modulus of elasticity in porous AlSi12, determined by [14]:

$$E_{P.(AlSi12)} = k \cdot E_{B.(AlSi12)} \cdot \left(\frac{\rho_{P.(AlSi12)}}{\rho_{B.(AlSi12)}}\right)^m, \quad (5)$$

Where:

$E_{P.(AlSi12)}$Young's modulus of elasticity of porous AlSi12 alloy [MPa],

$E_{B.(AlSi12)}$Young's modulus of elasticity of base AlSi12 alloy [MPa],

$\rho_{B.(AlSi12)}$Density of the base material [kg·m⁻³],

kConstant for calculation of the modulus of elasticity $k = (0,1 \text{ to } 4)$, [14],

mConstant for calculation of the modulus of elasticity $m = 2$ [14], $m = 1.5 \text{ to } 1.7$ [26].

Calculation of the coefficient of thermal conductivity of porous AlSi 12 alloy through a relationship [14]:

$$\lambda_{ALP} = \lambda_{B.M.} \cdot \left(\frac{\rho_{ALP}}{\rho_{B.M.}}\right)^a, \quad (6)$$

Where:

$\lambda_{B.(AlSi12)}$...Thermal conductivity base material AlSi 12 alloy ($\lambda_{B.(AlSi12)} = 150 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$),

a Constant ($a = 1.65 \text{ to } 1.85$) [14], $a = 2$ [26].

Based on the equations from (1) to (6), the selected values of properties of the porous materials were calculated and values are shown in Table 4.

Tab. 4 Values of aluminium alloy AlSi 12 porous material production squeeze NaCl into melt aluminium alloys

Properties of samples: 1, 2, 3			
Sample numbers	1	2	3
Average particle size sodium chloride [mm]	8 to 10	5 to 7	3 to 5
Density of sample from AlSi 12, (base material) $\rho_{B.(AlSi12)}$ [kg·m ³]	2650	2650	2650
Volume of sample AlSi 12, (base material), $V_{B.(AlSi12)}$ [m ³] D = 45.5 mm; d = 41.2 mm; h = 26.8 mm; sample 1; D = 46.5 mm; d = 42.3 mm; h = 25.0 mm; sample 2; D = 46.0 mm; d = 44.1 mm; h = 20.45 mm; sample 3.	$4.057 \cdot 10^{-5}$	$3.872 \cdot 10^{-5}$	$3.258 \cdot 10^{-5}$
Weight of sample AlSi 12, $m_{B.(AlSi12)}$ [kg] D = 45.5 mm; d = 41.2 mm; h = 26.8 mm; sample 1; D = 46.5 mm; d = 42.3 mm; h = 25.0 mm; sample 2; D = 46.0 mm; d = 44.1 mm; h = 20.45 mm; sample 3.	0.108	0.103	0.0863
Volume of sample of AlSi12 porous; $V_{P.(AlSi12)}$ [m ³]	$4.057 \cdot 10^{-5}$	$3.872 \cdot 10^{-5}$	$3.258 \cdot 10^{-5}$
Weight of sample AlSi 12 porous; $W_{P.(AlSi12)}$ [kg]	0.0380	0.0385	0.0354
Density of sample AlSi12 porous; $\rho_{P.(AlSi12)}$ [kg·m ³]	947	994	1086
Relative density of AlSi 12 (porous/base); $\rho_{REL(AlSi12)}$ [1]	0.36	0.38	0.41
Porosity of AlSi 12 (porous AlSi12 alloy) P [%]	64	62	59
Young's tensile modulus of elasticity AlSi 12 (porous AlSi12 alloy) $E_{P. AlSi12}$ [MPa]	958	1055	1260
Coefficient of thermal conductivity of AlSi 12 (porous AlSi12 alloy) $\lambda_{P.(AlSi12)}$ [W·m ⁻¹ ·K ⁻¹]	27	30	34

Note: $E_{B.M. (AlSi12)}$ - Young's module of elasticity, $E_{AlSi12} = 75\,000$ [MPa]; $k = 0.1$; $m = 2$; $a = 1.65$

3.2 Monitoring the structure of samples of porous materials

The connection of open cells in the structure of the AlSi12 alloy of porous aluminum materials was observed using the electron scanning microscope (Vega 3 Tescan, SEM HV 20.0 kV). The samples 1, 2 and 3 in Fig. 5 were selected for the identification of their porosity in a plan view. Figures from 6 to 8 show typical structures of the selected samples 1, 2 and 3 in details, where the porosity were observed using an electron scanning microscope.



Fig. 5 View of samples for monitoring cells of porous materials made of AlSi12 alloy (samples, 1, 2 and 3)

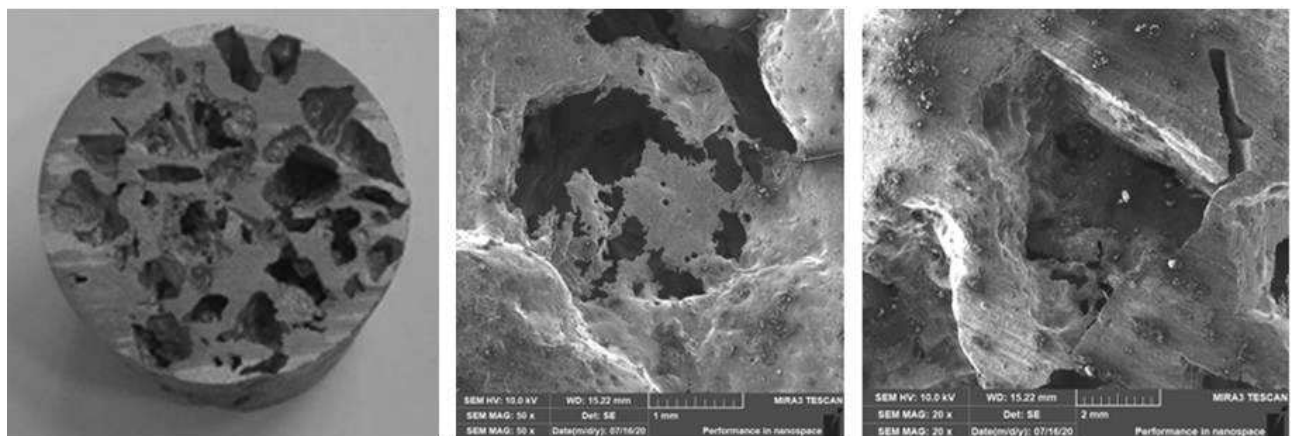


Fig. 6 View of the structure of sample of porous material AlSi12 alloy, sample 1

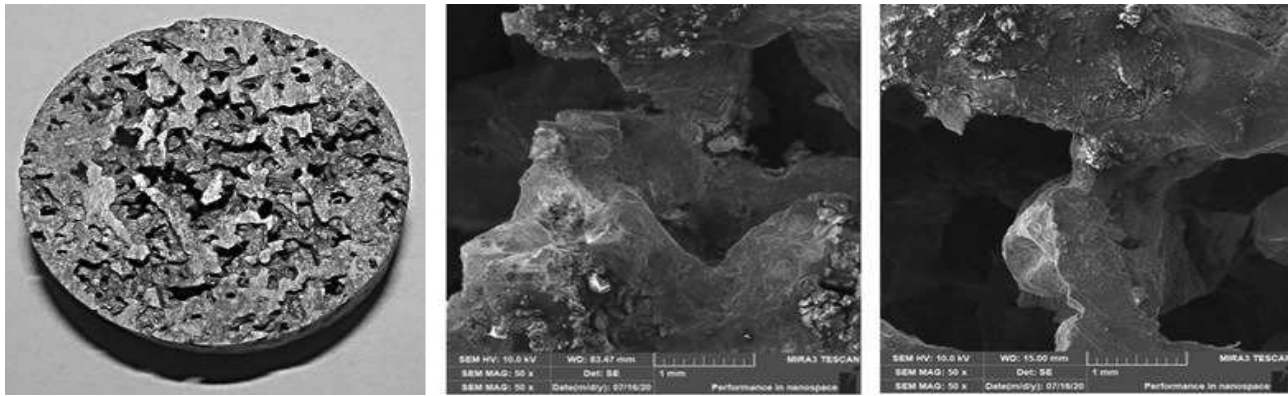


Fig. 7 View of the structure of sample porous material AlSi12 alloy, sample 2

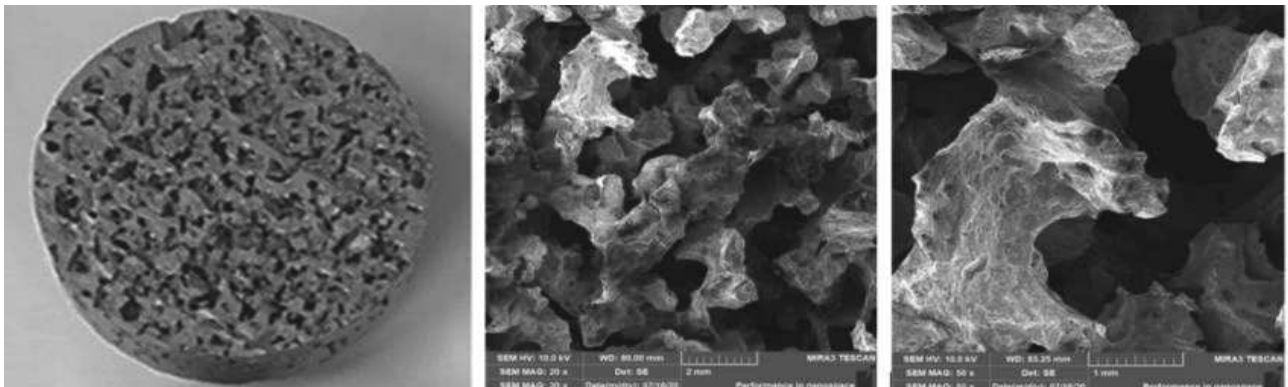


Fig. 8 View of the structure of sample porous material AlSi12 alloy, sample 3

3.3 Monitoring of mechanical properties of selected porous aluminium materials from AlSi12 alloy

The compressive strength of the produced samples was monitored on a TIRA Test tearing machine as is illustrated in Fig. 9,(left). This test was applied to the sample No. 1 and No. 2, i.e. using a sodium chloride particle size of 8 to 10 mm and 5 to 7 mm.

During the compressive strength test, the effect of porosity, resp. influence of cavity size on compressive strength of material was investigated. Figure 10 shows dependences of stress - strain for a sample with a porosity of 8 to 10 mm and for a sample with a porosity of 5 to 7 mm.

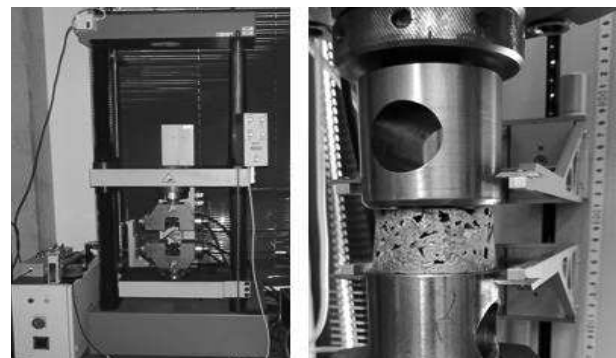
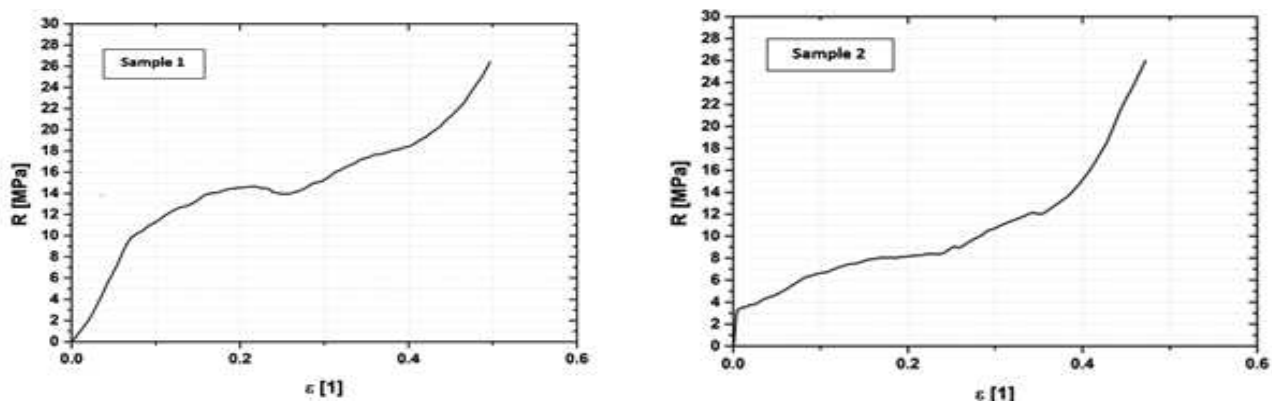


Fig. 9 TIRA device Test for measuring the strength of samples, on the left and detail of the pressure test of aluminium porous materials, on the right



Sample 1 - Young's tensile modulus, $E_{P(AISi12)-1} = 160 \text{ MPa}$;

Sample 2 - Young's tensile modulus, $E_{P(AISi12)-2} = 1027 \text{ MPa}$;

Fig. 10 Compressive strengths of aluminum porous materials from AlSi12 alloy, samples 1 and 2

4 Conclusion

The property values of these porous aluminium materials are not very well published. These materials are used mainly in the function of filters. The obtained results of the produced samples confirmed that porous aluminium materials of simple geometric shapes can be successfully used. In fact during the production process, the use of 50% by volume of sodium chloride and 50% by volume of aluminium alloy AlSi 12 was preferred with the possibility of application of sodium chloride particle with the specific size of 8 to 10 mm; 5 to 7 mm and 3 to 5 mm. At the same time, samples of porous aluminium material were obtained from an alloy with a porosity of 59 to 64% and a density of about 950 to 1085 kg·m⁻³. Young's modulus of same 1 is about 160 MPa. The calculation of the value of E according to equation (5) is 958 MPa, which is almost 6 times higher than the value obtained from the test at a pressure of 160 MPa. Using sodium chloride particles with a size of 5 to 7 mm (sample 2), the value of the Young's modulus of elasticity was calculated from the stress-strain curve, which is 1027 MPa. The value of the Young's modulus of elasticity calculated according to equation (5) is 1055 MPa. As can be seen from Fig. 10, the stress-strain curve of the porous aluminium material corresponds to the mild steel curve. The curve consists of three areas. The first area is the steep stress curve. Walls around the cavities are quite strong and contribute to a small deformation as can be clearly seen from Fig. 10 (right). In the second area, the stress-strain curve is slower, less steep with large strain. The lower strength of the walls around the cavities already contributed to this deformation. With increasing stress, cell walls are gradually deformed and collapsed and gradually the porous material begins to be compact (collect). In the third area, the already compact material is further deformed, so the stress rises steeper until its integrity is broken. Our compressive strength results confirmed the general assumption that the larger sodium chloride particles created larger cavities in the material and therefore the greater porosity. Thus, the porous material exhibits lower compressive strength.

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